ON A POSSIBLE REVERSAL OF DEEP-SEA CIRCULATION AND ITS INFLUENCE ON GEOLOGIC CLIMATES.[1]

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Among the multitude of subjects that drew illuminating thought from the cosmopolitan philosopher to whom we pay our homage, were the phenomena of the atmosphere and the ocean. Aside from atmspheric electricity, certain climatic phenomena were subjects of his special study, as we are to learn more fully in the course of these memorial exercises. But Benjamin Franklin was above all a student of human affairs and his physical inquiries were instinctively correlated with human interests. If, therefore, in treating a phase of oceanic circulation and its bearings on geologic climates, I associate my subject frankly with the interests of our race, I trust it may be assigned to a desire to bring my contribution into harmony with the spirit of the distinguished American philosopher of the eighteenth century.

The control of secular climates is obviously a condition prerequisite to biologic continuity. The preservation of a narrow range of temperature and a limited variation of atmospheric constituents throughout the millions of years of the biologic past was absolutely essential to organic evolution. Continued preservation for millions of years to come seems equally a condition precedent to an intellectual and spiritual evolution commensurate with the physical and biological evolutions that have preceded it. Only such a prolonged evolution of the intellectuality now just dawning gives full moral satisfaction to our conception of the sum-total of terrestrial history.

The narrowness of the range to which temperatures must be confined to permit progressive organic and intellectual evolution takes on its true meaning only when we recall that the natural tem-

[1] Presented by permission of the President of the Carnegie Institution under whose auspices these studies have been prosecuted.

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perature-range on the earth's surface is sixteen times as great as this, while that affecting the solar family is at least sixty times as great. For a hundred million years, more or less, this narrow range of temperature has been maintained quite without break of continuity, unless geologists and biologists are altogether in error in their inductions. On the further maintenance of this continuity hang future interests of transcendent moment.

So too the maintenance of a narrow range of atmospheric constitution, notably in the critical element carbon dioxide, has been equally indispensable. These two critical limitations of temperature and of constitution seem also to have been interdependently correlated with one another.

The climatic problem is as difficult as it is important. The factors are so many, so elusive, so imperfectly determined, perhaps even so imperfectly determinable, that the utmost patience and assiduity are a duty of the investigator, and the utmost charity of judgment an obligation of fellow scientists. I am persuaded, however, that tentative analyses of the tangle of factors are an indispensable aid to the future solution of the problem. One of the gravest difficulties confronting us to-day is the imperfection of observations and the inconclusiveness of experimentation; and this arises in no small degree from the lack of such patient preliminary analyses of the problem as shall bring into sharp recognition the occult things that are to be observed and the precise experimental determinations which alone can really aid in the solution. If the little contribution of this half hour shall have any value at all, it will lie in its suggestive relations to the larger problem of secular climates, past and prospective.

As this larger problem has recently assumed, with some of us, a phase much at variance with its more familiar aspects, it may need to be briefly sketched. It has been customary to assign to the primitive earth a climate quite beyond the Miltonian conception of Gehenna in its fiery intensity, and to predict an impending refrigeration scarcely inferior in antithetic supremacy. The familiar conception of the sum-total of atmospheric history as a decline from one excess to another as the sequence of thermal wastage, is a logical deduction from the hypothetical derivation of the earth from a gaseous or quasi-gaseous nebula through gravitative condensation. To some of us, however, such a derivation seems inconsistent with the dynamics of the present solar system, and an alternative hypothesis has been formulated to meet the supposed requirements of existing phenomena. The acceptance of this requires a reconstruction of the whole conception of geologic climates. The new view discards the primitive molten state as a necessary condition and presents the alternative of a slow growth of the earth by planetesimal accessions. This alternative involves a slow growth of the atmosphere also, until it reached a volume similar to the present, when its growth is assumed to have been arrested and thereafter limited by the interplay of opposing agencies. These agencies are thought to have held it ever since within so narrow a range of oscillation as to foster organic evolution. A continuance of the same control offers ground for hope of a perpetuation of conditions congenial to organic and intellectual life, through a period to which no definite limits can now be set beyond the presumption that there must ultimately be a limit. The inevitable cooling of a once white-hot earth plays no part in this prognosis. The agencies of atmospheric *maintenance* and *control* thus force themselves upon consideration as factors of supreme importance.

The assigned agencies of atmospheric *restraint* are molecular velocities, chemical combination and condensation. By virtue of the first, the lighter constituents are reduced to a minimum and all constituents are restricted within certain large limits. By virtue of the second, the chemically active factors are kept down to states of dilution compatible with organic evolution, while the inert elements have probably been permitted to increase steadily. By the third, the excess of water-vapor has been condensed into the ocean, which has probably increased rather than diminished through the ages.

The postulated agencies of atmospheric *supply* are accessions from without and emanations from within, of which Vesuvius is just now giving us an impressive illustration.

To the interplay of these opposing agencies of loss and gain is assigned the maintenance of the requisite narrow range of atmospheric constitution, of temperature, and of associated conditions. Under this general resetting of fundamental conceptions, the question of climatic regulation takes on very concrete aspects and presents specific lines of study.

Subsidiary to these narrow limitations, the recognition of pronounced variations is forced upon us by a growing mass of geologic evidence. Throughout most of the well-known geologic periods, the poleward distribution of life implies warm climates, even as high as 70° and 80° of latitude. How life of sub-tropical types could have survived the long polar nights is one of the most obdurate puzzles of the earth's climatology. It becomes all the more strenuous if we cast aside all resort to an early fervid state and a molten interior. Quite irrespective of primitive conceptions, however, the edge of the problem has sharpened as we have been forced to recognize that *between* the warm polar stages there were episodes of glaciation in strangely low latitudes. It appears necessary now to accept as demonstrative the evidences of extensive glaciation in India, Australia and South Africa in the midst of the later coal-forming stages of the Paleozoic era. The glacial beds lie even between coal beds of Permian or Permo-Carboniferous age; while, strangely enough, the areas of glaciation approach and even overlap the tropics of Cancer and Capricorn. And yet, figs and magnolias have grown in Greenland since, and mild polar climates are as well authenticated after as before this climateric glaciation. Less complete evidences from China[1] and Norway imply a very much earlier glaciation, falling in the oldest Cambrian or perhaps even pre-Cambrian times.

The climatic student seems therefore compelled to face oscillations within the known geologic periods ranging from sub-tropical congeniality within the polar circles, on the one hand, to glacial conditions in low latitudes, on the other, and these *in alternating succession:* while neither of these oscillations was permitted to swing across the narrow limital lines of organic endurance. There is little doubt that the ocean, the daughter of the atmosphere, is one of the most potential agencies in controlling these oscillations. It is one of its possible functions in such regulation that invites our present attention.

Some of the regulating functions of the ocean have long been

[1] Willis, "Third Year-Book Carnegie Institution," 1904, p. 282.

recognized. Certain less familiar ones have been brought under study in recent years by a few students independently. Schlœsing was perhaps the first to clearly recognize that the carbon dioxide of the ocean is an important agency in the regulation of the atmospheric content of this critical factor. As early as 1880[1] he advanced the view that the carbon dioxide of the atmosphere is in equilibrium not only with the free carbon dioxide absorbed in the sea water but through dissociation with the second equivalent of carbon dioxide in the oceanic bicarbonates. The sum-total of such free and loosely combined carbon dioxide available at present as a possible supply for the atmosphere may be some twenty-five times the present atmospheric content. Schlœsing held that any depletion of the atmospheric content would be followed by emanation from the ocean, and any excess acquired by the atmosphere would be followed by oceanic absorption, and hence great changes in the atmospheric content would only be brought about by reducing or increasing the large sum-total of atmospheric and oceanic supply. This was a contribution of the first order to the problem of atmospheric regulation. It is necessary for a geologist, however, to recognize that the exchange, and even the equilibrium itself, are dependent on geological and physical conditions. At periods in which the oceanic bicarbonates were most abundant, the amount of free and loose carbon-dioxide in the ocean may perhaps have reached thirty or forty times the present atmospheric content, while on the other hand it may have fallen to a very low figure when the ocean was depleted of carbonates. It is necessary also to recognize that the diffusion of gases in water, so far as it is covered by experiment, is a slow process, and computation seems to show that the supply of carbon dioxide to the atmosphere might be much too slow to offset its consumption under certain geologic conditions, unless effectively aided by oceanic circulation. The active superficial circulation immediately assignable to the winds would aid somewhat but its competency is limited. It was in an attempt to determine the functions of the deep-sea circulation in this interchange that the conceptions of this paper arose.

[1] "Sur la constance de la proportion d'acide carbonique dans l'air," *Comp. Rend.*, 1880, t. 90, p. 1410.

In an endeavor to find some measure of the rate of the abysmal circulation, it became clear that the agencies which influenced the deep-sea movements in opposite phases were very nearly balanced. From this sprang the suggestion that if their relative values were changed to the extent implied by geological evidence there might be a reversal of the direction of the deep-sea circulation and that this might throw light on some of the strange climatic phenomena of the past and give us a new means of forecast of climatic states in the future.

That the deep-sea circulation is now actuated dominantly by polar agencies is clear from the low temperatures of the abysmal waters, even beneath the tropics. It is a firm inference that cold waters creep slowly along the depths from the polar seas equatorward where they gradually rise to the surface and return on more superficial routes. This is not, however, yet a matter of observation and the courses pursued are unknown. It is perhaps more probable that they are gyratory or spiral and complex than that they are simple and direct.

The agencies that affect oceanic circulation include at least: (1) wind, (2) atmospheric transfer, (3) differences of salinity, and (4) differences of temperature, including freezing and thawing. The earth's rotation of course modifies the currents but does not actuate them.

1. The effect of the wind is superficial and familiar, and need only be considered here in so far as it affects the deep-sea circulation. Its currents constitute horizontal circuits, and their frictional effect upon the deep currents is probably slight and of a gyratory phase in the main. In so far as they are strictly horizontal, they doubtless favor equally poleward and equatorward movement in the abysmal waters. If there is a component of their sum-total that favors the piling up of waters in the polar regions, it must favor the present deep circulation. If the opposite is true, it must antagonize it. There seems no way at present to measure the relative amounts of these opposing tendencies. It is plausible enough to reason that the cold air from the polar regions would flow more largely at the base of the atmosphere than would the warmer air from the equatorial regions and that the polar winds would thus

antagonize the present abysmal circulation. But theoretical deductions are rarely sure-footed in these complex subjects. The balance of influence, whatever it may be, is probably so slight as to be negligible.

2. We cannot here attempt to follow empirically the transfers of water by evaporation and precipitation, but general inspection seems to indicate the nature of the average effect. The saturation point of the atmosphere falls progressively from the equator to the poles, and the actual humidity runs roughly parallel to it on the grand average. Poleward movement of the atmosphere leads therefore to a lower content of moisture; equatorward movement to a higher. As the acquisition of moisture lags behind the capacity to hold it, it is a rather firm inference that precipitation exceeds evaporation in the high latitudes and that evaporation exceeds precipitation in the low latitudes, on the grand average. The bearing of observational data is of the same import. The result of these ratios of precipitation and evaporation is a raising of the ocean surface by fresh waters in the polar regions and a lowering of it in the low latitudes accompanied there by concentration of saline constituents. Considered alone and ideally, this should give a slight equatorward gradient and a flow of fresh surface waters in that direction. These fresh waters, however, mingle with the superficial sea waters and involve a movement of these also toward the equator. So far as these affect abysmal movement, they antagonize the present circulation.

3. In so far as evaporation exceeds precipitation in the low latitudes, it results in an increased salinity of the superficial waters and a tendency of these to sink and flow poleward to replace the salt waters carried equatorward by the fresh waters as just observed. If these were the only factors it seems clear that the deep circulation would be poleward.

4. On the other hand, the lower temperatures of the high latitudes increase the density of the water and tend to cause it to sink and flow equatorward. But the low temperatures affect primarily the superficial stratum which is freshened by the superior precipitation of the high latitudes, and both computation and observation show that cold fresher waters may float upon warmer saline waters.

A large part of this cold superficial water flows away in surface currents to lower latitudes.

In view of these complications, the precise mode by which polar agencies control the deep circulation is much less obvious than it might at first seem. There is ground to suspect that the formation and melting of ice is an important factor. In freezing, the salt and gases of the surface layer are largely forced out into the underlying layer. If the surface layer has an average degree of salinity, the underlayer is super-charged, and being also cold, must tend to sink. On the borders of the ice-covered tracts where the precipitation and melting are considerable and where adjacent polar lands pour in much fresh water, the surface layers are so much fresher than the average sea-water that the concentration of salinity by freezing does not overbalance the original freshness. But in those polar regions where there is no inflowage from the land, where precipitation is slight and almost wholly snow, which accumulates on a previously frozen surface and absorbs most of its own summer melting, and where the ice is borne away to lower latitudes and the waters arising from it do not redilute the concentrated waters, it is believed that a sufficient degree of saline concentration, combined with depression of temperature takes place to cause an effective downward movement. This is believed to cooperate with diffusion and conduction in giving the lower body of polar waters the superior gravity which actuates the abysmal circulation. The sea immediately bordering Antarctica and that lying northwest of Greenland seem to furnish these conditions. Moss[1] and Krogh[2] independently have found that at times of northwesterly wind, the air west of Greenland contains about double the usual content of carbon dioxide. This I have suggested may come from waters overcharged with it by the freezing of the overlying layer.

It is not to be inferred, however, that the deep-sea waters derived from the polar regions exceed in salinity the waters of the evaporating tracts of low latitudes, but merely that by this concentration through freezing conjoined with low temperature and modified by

[1] Moss, "Notes on Arctic Air," *Proc. Roy. Dublin Soc.*, Vol. II, 1880.

[2] Krogh, "Abnormal CO_2 Percentage in the Air of Greenland," etc., *Meddelelser om Gronland*, Vol. XXVI, 1804, pp. 409–411.

diffusion and mechanical mixture, water of superior gravity is derived and that this controls the abysmal circulation.

Dr. Otto Pettersson, in an elaborate article, supports by experiment and observation the theory of Bjerknes, that the *melting* of the polar ice also promotes circulation, both superficial and deep-seated, but I can only make reference to this here.[1]

A survey of the existing temperatures and salinities of the ocean also makes it clear that the battle between temperature and salinity is a close one and that no profound change is necessary to turn the balance. The combined results of the many polar expeditions have shown that in the high latitudes of both hemispheres there is a superficial sheet of water two hundred to three hundred meters deep that is colder, but lighter, than that below, because it is fresher. It floats upon a warmer, more saline body of water below. This has been specially demonstrated by the investigations of Nansen.[2] This layer of coldest water moves to lower latitudes superficially in the main, showing that coldness alone is not determinative.

In the open Pacific and Indian oceans hydrostatic equilibrium must be very closely maintained, because of the slight resistance to adjustment. It is shown by the charts of Dr. Alexander Buchan[3] that the concentrated warm saline waters form inverted cone-like masses that reach down some four thousand feet or more. It thus appears that they lie in the same horizons as great masses of colder waters which their salinity must counterbalance. Less striking phenomena of similar import mark the evaporating areas of the north and south Atlantic. The equatorial tracts of freshened waters arising from high precipitation are scarcely traceable to half the depth. This seems to imply that in the low latitudes increased density due to evaporation is more potent than freshening by precipitation, in harmony with theory as already set forth, and that the density due to salinity is not greatly over-matched by the low tempera-

[1] "On the Influence of Ice-melting on Oceanic Circulation," *Geog. Jour.*, XXIV., 1904, pp. 285–333.

[2] "The Norwegian North Polar Expedition, 1893–1896, Scientific Results," Fridjof Nansen, Vol. II, Oceanography of the North Polar Basin.

[3] "Challenger Reports," Summary of Results, Pt. II, Appendix, Rept. on Oceanic Circulation.

ture density of the Antarctic regions from which the Pacific and Indian oceans are not separated by appreciable barriers.

An interesting illustration of the close balance between salinity-density and temperature-density is presented by the saline waters that issue from the Mediterranean in which evaporation is in excess of combined precipitation and inflow from adjacent lands. As a result, the concentrated waters that form the deeper body of the Mediterranean creep out through the bottom section of the Straits of Gibraltar, while the upper section is occupied by a compensating inflow from the Atlantic. Although the straits are shallow, the out-creeping current does not appear in the upper horizons of the adjacent Atlantic waters, according to Buchan's charts, but descends to depths of three thousand to five thousand feet before it finds a horizon of density-equilibrium. It then spreads westerly in a great spatulate wedge across the north Atlantic and occupies the larger part of its area between the depths of four thousand and five thousand feet. (See the maps of Buchan.) It is warmer and more saline than the normal oceanic waters at its horizon, and lies on colder but less saline waters below.

These and similar phenomena point to a notable closeness of the balance between the density effects of salinity and of temperature respectively. More saline but warmer waters both overlie and underlie less saline but colder waters. On the whole, however, at present, the temperature effects are dominant and cold waters occupy the abysmal depths of all the great oceans.

A comparative computation of salinity-effects and of temperature-effects on density, from such data as are now available, leads to a similar conclusion relative to the closeness of balance between the opposing agencies, but this cannot be entered upon here.

Now, as previously remarked, the geological record gives good evidence that in the majority of known periods the temperatures in the polar regions were subtropical or warm temperate. Freezing must apparently have been a trivial factor, if not quite absent, and low temperature was robbed of its chief densifying effects. Evaporation in the zones of descending air currents in low latitudes must apparently have been operative, in some degree at least, to furnish the geological agencies which the record implies. Deposits of salt and gypsum in not a few periods testify directly to regional aridity. The most marked of these are, to be sure, referable to the periods of glaciation, but many of them have no such assignable association.

In these periods of warm polar temperature there is reason to believe that the high-latitude temperature-effects fell below the low-latitude concentration-effects and that therefore the deep oceanic circulation was actuated by the dense waters of the evaporating tracts. These may then be supposed to have slowly descended and crept poleward, acquiring a trivial amount of heat from the earth's interior and loosing some to the waters above, but substantially maintaining their temperatures until they rose to the surface in the polar regions and gave their warmth to the atmosphere. Aided by the enshrouding mantle of vapors that must have arisen from such a body of water, it is conceived that the mild temperatures requisite for the maintenance of the recorded life through the polar nights may have been thus maintained.

If this be granted, however, it is wise to note that this is not a radical solution of the climatic problem, for a fundamental cause for the conditions that brought on freezing at one period and prevented it at others is prerequisite to the postulated influence of these in the reversal of the abysmal circulation. At the best, our suggestion offers only an auxiliary agency in the control of secular climates. Some more fundamental agency or agencies must be sought.

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